CASE STUDIES IN TURBOMACHINERY OPERATION AND MAINTENANCE USING CONDITION MONITORING

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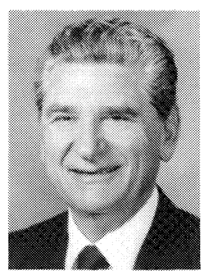

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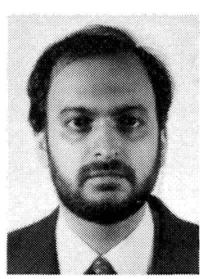

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ABSTRACT

With exceedingly high downtime costs and the need for efficient operation of turbomachinery, integrated condition monitoring, wherein a number of health parameters are analyzed, is becoming increasingly popular in process plants and in utilities. Most operational problems can be diagnosed by developing a correlation among several key operating parameters. A wide range of condition monitoring approaches are available and this paper shows how several approaches can be used in conjunction with one another to solve operational problems. Several case studies pertaining to gas and steam turbines and compressors are presented. A matrix of condition monitoring techniques is provided and case studies are presented. Finally, future trends in the area of condition monitoring are presented.

INTRODUCTION

Process and utility industries routinely diagnose operational problems, prevent equipment malfunction or failure, determine optimum equipment operating conditions, schedule maintenance, and repair or replace defective parts based on the information obtained from condition monitoring systems. A recent survey by Electric Power Research Institute (EPRI) has indicated that the use of diagnostic monitoring system in the utility industry alone would enhance plant availability by two percent which in monitory terms translates to $400 million per year in US alone. If process industries are included, an estimated ten fold increase in savings could be obtained.

A variety of condition monitoring systems are in use in industry, each with a specific application. They can be broadly classified as vibration and acoustic, aerothermal performance, and oil and debris monitoring systems. The choice of a monitoring system is based on investment and payback considerations. Thus, there are hand held, micro, and mainframe computer based monitoring systems each for a different level of sophistication and investment. Among the portable and microcomputer range versions there are portable vibration signature collectors, lubricant oil sampling devices, acoustic leak detectors, thermography, etc. A combination of these portable units are also in use; vibration and oil analysis are combined to monitor bearing condition. Acoustic and thermogaraphic units have been useful in detecting valve leakages, identifying hot spots on boilers, valves, etc. While these units are for specific use, a comprehensive overall condition monitoring system utilizes both the vibration and performances data to report accurately the current plant status, to diagnose any malfunction or to predict the future condition of the plant.

Due to the complexity of critical turbomachinery operation, a comprehensive condition monitoring system should use both steady state and transient data. Vibration and performance data are used to accurately estimate engine condition. The main reason for utilizing both performance and vibration data is to distinguish between mechanical and aerodynamic induced vibration signature. Performance monitoring becomes especially crucial in evaluating performance retention or degradation rate of a component and hence directly deals with economics of operation. Performance monitoring is useful in detecting compressor, combustor, and turbine malfunctions. Vibration monitoring and bearing temperature analyses on the other hand are useful to evaluate the mechanical health of the machine. Bearing failures, rotor imbalances, etc., fall into this category.

Traditionally, condition monitoring system were used for safe equipment operation and to prevent equipment failure. New sensors, instrumentation, and enhanced capability of computers combined with economic pressures have introduced an additional application: operating equipment at its maximum efficiency. A key issue is how one *retains* performance and limits degradation. Some important factors that are of relevance to condition monitoring are:

- *Fuel Costs*— Fuel costs constitute a large part of the total gas turbine life cycle costs. The annual fuel cost for a 25 MW gas turbine is between seven and eight million dollars. Several forward looking corporations now demand that condition monitoring systems be used for performance degradation control.
- *Availability*— This is a strong function of system design, fuel used, and environmental factors. If properly implemented, condition monitoring can help in the attainment of high availabilities.
- *Maintenance*—Hot section maintenance and inspection of a major source of unavailability in utility gas turbines.

CONDITION MONITORING TECHNIQUES

Condition Monitoring Techniques

A review of the major engine health monitoring techniques used are presented here. Available techniques and details on their implementation and integration are provided in Table 1 [1].

The choice of the condition monitoring philosophy (on line *vs* off line), particular approach and the diagnostic technique should be based on specific plant operational objectives, location of the machine (offshore, unmanned operation, etc.), criticality of machines, and the failure modes experienced. As *implementation* and acceptance of a condition monitoring system is a key issue, plant operational practices and maintenance philosophy must be considered at the early stages of a condition monitoring project.

Performance Analysis

Modern turbines and compressors are monitored comprehensively for control and protection purposes. In fact, there is now a convergence between control systems, protection systems and condition monitoring systems. Interfacing (or combining) a condition monitoring system with a modern control/protection system is often only a matter of having an RS 232 or similar connection. This means that most of the information required for aerothermal analysis is readily available. Some machines may require the addition of some sensors for comprehensive aerothermal performance analysis. Several gas turbine operators are installing torque couplings on compressor and pump drives. Torque meters are now quite reliable and have accuracies of better than 0.75 percent. They can often give indications of surge and torsional vibrations and provide valuable information from a condition monitoring standpoint.

The aerothermal performance of a gas turbine provides valuable insight into its operating condition. It is important to integrate such a system with vibration analysis as several vibration problems are manifestations of underlying aerothermal problems. Some problems that can be detected/solved by an integrated condition monitoring approach include rotating stall in axial flow compressors and in centrifugal compressors (both in inducers and diffusers), rotor bows due to rapid temperature ramping, distortion or fouling related surge events (intake distortion), and plugged nozzles.

Table 1. Condition Monitoring Technologies and Their Integration [1].

TECHNOLOGY	GENERAL COMMENTS AS APPLIED TO GAS TURBINES	ON-LINE /OFF-LINE	FAILURE MODES/ DEGRADATION DETECTABLE	DATA PRESENTATION AND ANALYSIS	APPROACH TO INTEGRATING WITH OTHER CONDITION MONITORING DATA
VIBRATION ANALYSIS	By far the most popular technique for condition monitoring. Use proximity probes for journal bearings and accelerometers for detection of high frequency problems. Some manufacturers make special probes to monitor rolling bearing bearings. This technique has been applied with success to both steady state and transient data. Included herein are techniques such as shaft position monitoring, phase angle analysis etc. Torsional vibration is also a valuable diagnostic indicator. Torsiographs have been used for diagnostic purposes but are not full time analysis devices.	On-line systems are important for critical machines. Walk around data collectors have also been used.	Wide range of rotor dynamic and resonance related problems such as unbalance, misalignment, looseness, bearing problems, instabilities etc. Also possible to get qualitative information on some blading problems, and some performance related problems.	For diagnostic purposes spectral representation and time waveform analysis is important. Phase angle analysis and orbits are also very valuable. Interpretation is of importance and requires some skill. Meaningful trending is important taking into account dependance of certain factors such as load, RPM etc.	In order to view meaningful trends, baseline comparisons should be made to ensure similar power levels, &/or speeds. Corroborative trending with other mechanical parameters is invaluable. Bearing vibration may be checked with bearing temperature, thrust position with thrust bearing temperature and other operating conditions (eg. Pressure ratio). Step changes in vibration should be evaluated in context of process changes, lube oil conditions. Certain vibrations such as seal oil induced vibration(≈40-50%RPM) can suddenly occur at a specific high load condition (on centrifugal compressors). Other problems such as insufficient tightness in bearing liner, cap or casing can appear or disappear with small changes in speed.
DYNAMIC PRESSURE ANALYSIS	This is an important tool though not often employed. Dynamic pressure can be measured at compressor locations or at the combustor. Can provide useful information regarding aerodynamic problems, instabilities, stall inception and at times blading damage. Another useful dynamic measurement is by strain gauges for blading vibration and stress. This is not however an approach that can be used for continuous operation.	Would require on-lin monitoring because problems under consideration are very erratic and can occur very rapidly.	can be useful to detect problems such as pulsations, surge, stall, rotating stall, fouled conditions, blading problems etc.	Data can be viewed on an oscilloscope or by use of a RTA. Similar data presentation to vibration analysis as data is essentially dynamic. Qualitative evaluation is also important.	Useful when correlated with general performance parameters (flow , Pr ratio, water injection level, etc.) Correlate with vibration behavior at both high and low frequencies. Pulsations can be most troublesome when associated with resonances. Can be synthesized with noise analysis - often a low frequency rumble of a beat type phenomena. Pulsations can cause serious problem during surge.
MECHANICAL ANALYSIS	Included herein are a host of techniques and approaches such as bearing temperature measurement, casing differential expansion growth, ultrasonic detection of bearing wear and all analyses relating to the performance of the lubricating system and associated heat exchangers.	Can be either on-line or off line. For bearing temperatures, a rapid scan rate is required to detect transient problems such as surge, water ingestion etc.	Bearing distress or distress in lu be oil systems.	Data can be presented in terms of tabulations or trends. Trend data may require some formof normalization. This is very parameter specific.	Bearing distress should be correlated with vibration, oil condition, debris analysis. In some cases, lube oil and bearing temperatures can be checked against acceptance zone plots which may be based on SHP, N1 etc. This is important with gearboxes where bearing temperatures may be highly load dependant. The effects of lube oil pressure and temperature can also be varied to see the effect on certain problems such as bearing and support excited vibrations, whirls, oil seal induced vibration, friction induced whirl and dry whirl
BORESCOPE NSPECTION (and other visual techniques)	An exceedingly important facet of condition monitoring and provides invaluable information of hot sectioncondition. Included here are the "common sense" type of visual and walk around inspections. It is exceedingly important th t troubleshooters do not loose the feel for machinery. Items such as feeling bearing caps, checking for foundation looseness, looseness in the bearing support system, obvious signs of misalignment and coupling problems should not be overlooked.	off-line inspection	Wear, cracks, hot section distress, abnormal fouling, heavy oxide deposits, missing blade tips, cracks, corrosion, erosion, coating flaking, FOD/DOD	Documentation is via photographs or video. Analysis by an experienced individual required. Useful as an aid to making difficult value judgements.	This information must be considered qualitatively with other condition monitoring data. The synthesis is therefore done by the engineer and involves value judgements.
NOISE ANALYSIS	Has been applied to helicopters but is not used extensively on rotating machinery for diagnostic purposes. However, some recent work has shown its use in troubleshootng of steam turbin s. The use of microphones in gas turbine inletducts has lso been used for rub detection during shutdown. On a simple level a mechanics stethoscope can also provide useful for detecting rubs during shutdown (creep induced)	Can be either off-line or on-line. Noise analysis equipment has been used for specific troubles ootingwork and not for continuous monitoring.	Wid rangeof problems such as gearing problems, airflow distortion, etc.	Can be analyzed in terms of frequency content using a RTA	Can be valuable for corroborating evidence in case of aerodynamic excitations, flow induced vibration and gearbox problems -intermediate and frequencies associated with the gear mesh (also for casing drumming)
SPECTROMETRIC OIL ANALYSIS PROCEDURE [SOAP]	SOAP has been applied in marine, industrial and other applications. Requires the regular collection of oil samples. Care must be taken during sample transportation. Good at detection of fretting, sliding wear, micropitting and water ingress. Unable to detect cracks or fractures that do not release tell tale debris. An lysis costs much cheaper than ferrography. Limitation of technique is that it gives no indication of particle size and cannot be used for sizes greater than 10μ. Another problem is the time between sampling and analysis.	This is an off-line approach and involves taking of oil samples.	Wear particulates in the lube oil system	Requires experts to analyze. Sophisticated analysis equipment required.	Use along with other indicators of wear such as vibration, bearing temperature etc.
PERFORMANCE MONITORING AND GAS PATH ANALYSIS TECHNIQUES	Important specially for large critical applications or in situations where energy costs are of importance. Several mechanical problems are manifestations of aerodynamic problems. We include under this head items such as trending, monitoring of EGT (or ITT) spreads and profiles. It is important to view the data both quantitatively and qualitatively. This can include the use of performance map based data analysis, checking of VSV schedules etc. Also included here are a host of performance related techniques related to *transient behavior*.	Can be performed in either an off line mode or on-line. Normalization nd correction of dat i important for meaningful calculations.	Deterioration in performance. The extent to which faults are isolatableto specifio components depends on the sophistication of data analysis, instrumentation integrity and several practical factors including symptom masking and data scatter effects. *Transient analysis* of aerothermal parameters is useful to detect a host of problems rel ting to the hot section, start ignition system nd several other problems.	Data can be presented in terms of tabulations, performance maps or trends. Trends are valuable to detect deterioration provided some form of data normalization is done to discriminate between off-design effects and derioration effects.	Corroborative trending with vibration is often very valuable. Examination of effect of speed on vibration is most important for diagnostic purposes. Examination of performance data when there is a step change in vibration is important. Rapid starts, rapid loading can induce bows, excessive temperatures can set up casing distortions and induce misalignment.foulants on the compressor can cause increase in unbalance and upon shedding, can cause step change in vibration.
FERROGRAPHY	A labor intensive technique restricted to ferrous metals. Seems to work of well for ball bearings. Can provide warning prior to detection using vibration.	Off line	Wear	Requires the use of optic a densitometer or high resolution icroscope. Analysis is via ferrograms. Skilled analyst required o interpret data. Some automated systems using image analysis have been developed.	Use along with other wear indicators for corroborative evidence
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MAGNETIC CHIP DETECTORS	Often a complementary technique used with SOAP. Chip detectors have to be removed at periodic intervals. Picks up particles typical of spalling and fretting. Only picks up magnetic material. Oil monitor filters will pick up non-ferrous debris as well. Optimal location of chip detector is often traded off for accessibility. Risk of improper installation (or non installation ofplug) is significant due to periodic removals. Introduction of fine filtration can negate effectiveness. As a practical matter, MCDs have been applied to aeroengin s (see oil debris monitoring)	Off-line. Requires periodic inspection.	Wear in oil wetted parts.	Visual inspection. Data (count) can be trended. Larger particles can be analyzed via microscopic examination (or SEM).	Usewithoth r indicators suc h as vibration.
OIL DEBRIS MONITORING	Looks at metal debris with sensors located in the scavange lines. Appropriate for gearboxes and for engines utilizing rolling elemen t bearings. Some sensors have been developed that are non intrusive. Has been suc essfully applied to aircraft, marine and industrial gas t rbines. Can detect ferrous debris in a wide range of sizes. Digit l display of counts av ilable.	can beon -line. Commercial on-line monitor ing systems available.	Wear	Digital displays and trend capability exists. Particles can be classified by size and num r.	Use with other wear indicators
USAGE MONITORING	Applied to lifed p rts that are subject to LCF and Creep. Usage algorithms can vary in complexity and typically, a compromise is forged between simplicity and accuracy. This has been extensively used in the maintenance managementof aircraft engines.	Data has tobe gathered by an on-line system to account for engine excursions, cycles etc.	Damage to disks, hot section blading and other lifed parts.	Usually requires design equations involving transient thermal stresses and complex empirical/experimental d ta ondamage as essment. More difficult with combined damage mod s suchas creep, thermal fatigue, corrosion etc.	Hot section component life is important and should be integrated with other condition monitoring parameters and off course, borescope inspections. In land basedgas turbines, someestimates c n be made based on the number of starts, trips and by accumulating engine time at different EGTs. A hot end pyrometer givesvaluableinformation on hot section temperature.
PYROMETRY	An important technology which should become more popular. It en bles determination of hot section metal temperatures. Can be used for control purposes. Valuable diagnostic tool that has been used on an on-line basis. Enables determination of improper cooling, excessive hot section life consumption and temperature profile problems.	Can be either off-line or on-line. Measurement by a hand held pyrometer ispossible. For critical machines, on-line prefered.	Blade cooling problems, poor temperature profiles, improper controlof firing temperature etc.	Can have co puterized readouts and graphic capability to get da a on blades, peak temperatures, and excursions from average temp, max blade temperature etc.	This data can be integrated with aerothermal analysis to provide an insight to hot section condition and for maintenanceplanning.

Further, this technology provides insight into how efficiently fuel is being utilized and thus, facilitates significant fuel savings if degradation is controlled. The authors include within performance analysis items such as EGT spread monitoring. This provides insight into hot section health. Actions such as this can significantly extend hot section life. Excessive spreads can occur due to a variety of reasons including excessive air leakages, blockage of nozzles, and cracks in the combustor liner/transitions.

Transient Analysis

There is considerable work being done in the area of transient analysis relating to both performance and vibration data are presented [3, 4]. Significant condition monitoring information is available by examining the profile of startup acceleration, coast down times, EGT response during light off, and other transient behavior.

Vibration Analysis

Vibration is a good indicator of machine mechanical health. With the correct choice of sensors and analysis techniques, vibration analysis is an excellent condition monitoring tool It is further enhanced when used in conjunction with other condition monitoring techniques. Some turbine suppliers provide the minimum sensors (in terms of numbers, frequency ranges, etc.) with the main objective of protecting the turbine from catastrophic failure. These sensors are not always successful in meeting this minimum objective. Several manufacturers will provide one or two accelerometers or seismic probes, often filtered to cover only the unbalance frequency (1 × rpm). Thus, the operator will often have to add sensors to get the best information for a good maintenance strategy.

Experienced troubleshooters will most often review the vibration data in *conjunction* with performance data to arrive at a "root cause" of a problem.

Dynamic Pressure Analysis

The use of dynamic pressure transducers has worked well to detect certain blading instabilities and compressor instabilities. This is an important facet of condition monitoring that has not received much attention.

Lube Oil Debris Analysis

A number of methods are currently available. Several aeroengines have magnetic chip detectors. Debris analysis has been most valuable on gearboxes and engines having rolling element bearings. A wide range of debris analysis techniques are available which can be both intrusive or nonintrusive.

Borescope Inspection

This is an important and valuable condition monitoring tool. (Borescope inspection can show up component cracks, erosion, corrosion, and buckling.) It is usually carried out at fixed intervals dependent on the machine with a video camera being used to record results. Borescope inspections are usually very quick and result in a minimum loss of turbine availability. It is important to have well trained personnel and clear cut procedures to ensure full coverage of the critical components. By using a video camera to record the inspection, one can enlist expert outside help to interpret the data. Eddy current checking is also done to detect cracks.

Usage Monitoring

Experience has indicated that a mere time count of life limited parts is not effective. Life is strongly dependent on the manner in which the engine is used (EGT history, number of starts and trips). The algorithms to calculate life usage are typically proprietary and require the knowledge of detailed design information. Because of this, it is difficult for industrial users to conduct any form of sophisticated usage monitoring.

Optical Pyrometry

By use of an optical pyrometer, it is possible to actually measure the metal temperatures of the first stage nozzles and rotating blades in a gas turbine. It is possible to obtain profile data from such a sensor.

Integration of Condition Monitoring Techniques

In order to plan maintenance for machinery problem rectification, one requires good insight into the operating condition of the machinery. With predictive maintenance, small incremental maintenance actions are used to delay the need for major maintenance intervention. For example, if ignored at an early stage, an increasing temperature spread in the combustion/turbine module may lead to premature failure of the first stage nozzle or even turbine blades. Maintenance action such as nozzle balancing can alleviate the problem. Sometimes, a combination of symptoms may be needed to pinpoint problems. A broken inlet guide vane mechanism, may cause increasing vibration and loss of compressor efficiency or possibly even surge.

Blading vibration and failures are one of the most complex problems in gas turbines due to the complicated blade dynamics and interaction of factors such as blade quality, environment (salt, temperature), erosion/wear, and fatigue effects. An integrated condition monitoring approach involving performance and vibration monitoring can be of help here. While vibration and performance monitoring cannot predict blade failures, often the underlying causes (air flow distortion, surge, nozzle bowing/blockage, etc.) can be detected, thus providing a chance to avoid the failure. The use of performance and vibration monitoring for reduction of blading problems has been described [4]. There has also been work done in the area of using dynamic pressure to detect blading problems.

Diagnostic Approaches

Diagnostics have been traditionally based on fault matrices or fault trees. In the last decade, expert systems have become popular. Some of the skepticism towards expert systems occurs because engineers believe that their long experience with machinery diagnostics cannot be summed up in a few rules of inference, no matter how powerful the inference machine. Expert systems generally imply a deterministic approach to machinery behavior. In reality, chaotic rules are often more appropriate. A machine may run perfectly well at one set of conditions but may *suffer seriously from a small change in these conditions. This is certainly true of some high discharge pressure compressors.* Expert systems are of use in dealing with sub-problems such as trending, data validity checking, and diagnostics. They are also valuable in integrating condition monitoring data in order to obtain meaningful diagnostics. A review of possible roles for expert systems is made by Doel [5].

There has recently been considerable work done in the area of the application of neural nets for monitoring and diagnostic applications [6, 7]. The training of a neural net may, however, require a considerable number of faulty engines. Another computer related technological development is the use of hypermedia, which could provide users with fast access to text and figures related to troubleshooting and maintenance of gas turbines.

For a new class of machines, tuning and modifications of standardized machine train based fault matrix diagnostic procedures, alarm and danger limits. etc., are necessary. Data for diagnostic tuning for new machines are typically obtained from condition monitoring systems [8]. In many cases, analysis procedures are used to simulate the effects of various faults on component performance models of newly introduced gas turbines, in order to improve the confidence level of diagnostic procedures obtained from fine tuning existing diagnostic procedures. Stage stacking method of fault simulation [9] has found wide acceptance in evaluating performance retention and simulating fault diagnostics. This procedure has the advantage of modifying the baseline stage characteristics to represent different fault types. Stacking of the stage characteristics shows the effect of a fault on a component performance (such as compressor or turbine). Matching calculations permits evaluation of the effect of fault on overall compressor characteristics.

CASE STUDIES

Maintenance and Overhaul of an Off-Shore Gas Turbine Compressor Train

Typically, major overhaul on a gas turbine unit can take several weeks to few months. Scheduling and operational constraints at times override scheduled maintenance. Until a decision to schedule an overhaul can be made, it is important to monitor the gas turbine unit for safe operation. A reliable comprehensive condition monitoring systems aids in safe gas turbine operation, till scheduled overhaul is logistically feasible, or if monitoring data does not indicate a distress. This case pertains to a gas turbine unit rated at 22.4 MW (ISO) driving a back-to-back configured centrifugal compressor [1].

The number 1 bearing of this turbine exhibited an increase in vibration that was picked up on the condition monitoring system and analyzed as unbalance. The machine had run for over 40,000 hr since its last major inspection and the performance of both the gas turbine and the pipeline compressor was poor, which was ascertained using a condition monitoring system. A decision was made to dismantle the turbine and gas compressor for an investigation. The 16 stage gas turbine axial compressor was found to have foreign object damage (FOD) on the first eight stages. The latter six stage compressor blading was severely eroded. The rotor was sent to repair. A spare rotor taken from another gas turbine was installed to replace the damaged compressor.

A trend is shown in Figure 1 in turbine ISO corrected horsepower, which indicated a decline prior to overhaul. The recovery after the overhaul is evident. A reduction in gas turbine compressor pressure ratio is shown in Figure 2 with time and the improvement attained when the replacement rotor was installed. Flow and polytropic efficiency improvement obtained in pipeline compressor after the overhaul are shown in Figures 3 and 4. Both these improvements were attributed to compressor cleaning and replacement of interstage seal. An improvement of about 40 percent

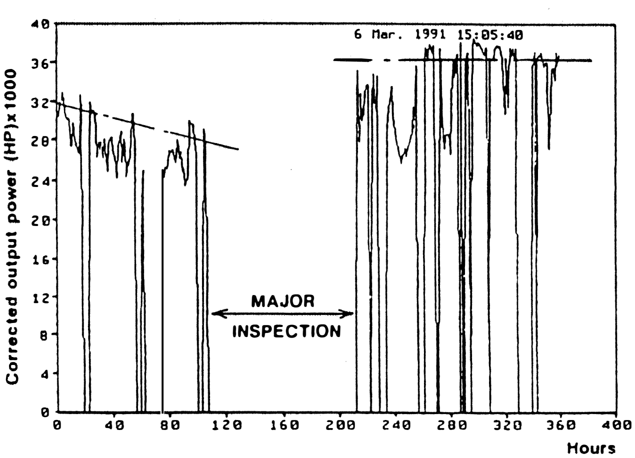


Figure 1. Turbine Corrected HP Before and After Major Inspection [1].

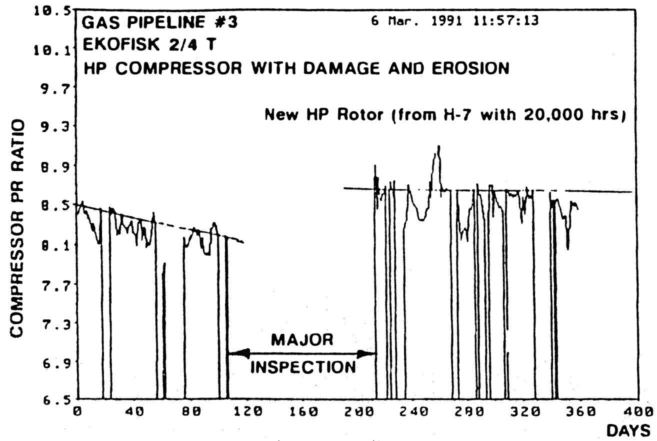


Figure 2. Recovery in Axial Flow Compressor Pressure Ratio [1].

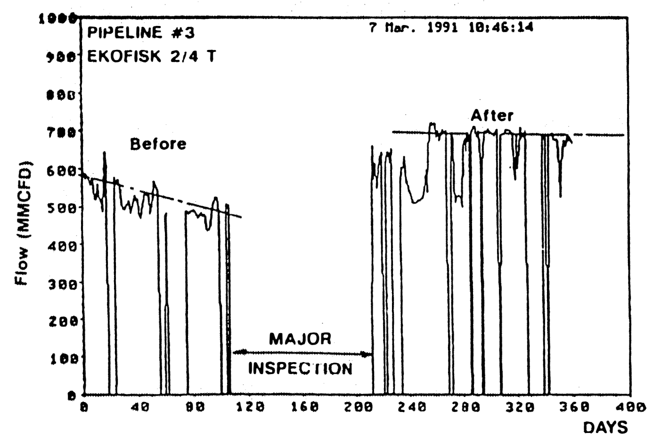


Figure 3. Pipeline Compressor Flow Capacity [1].

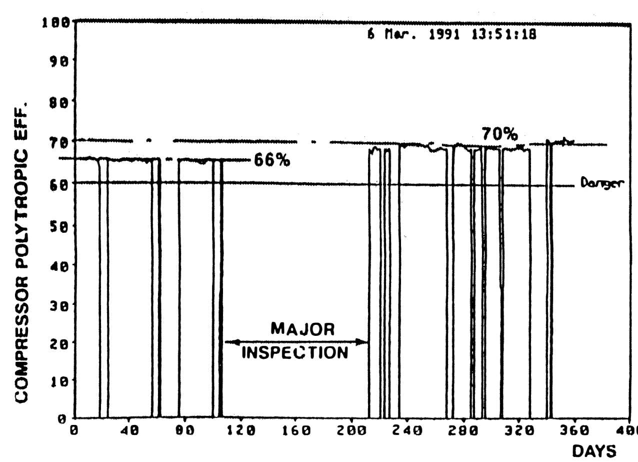


Figure 4. Polytropic Efficiency of Pipeline Compressor [1].

in the vibration level at the compressor inboard bearing was also noted, as shown in Figure 5.

A severe vibration of the gas turbine bearing number 1 was noticed after post overhaul restart. Since spare compressor rotor and turbine rotors were checked and well balanced prior to overhaul, the coupling was checked for any problems. It was found that inadvertently, an old accessory coupling (with high unbalance) had been installed instead of a new one. Replacement of the old coupling with a new one reduced vibration levels dramatically, close to 75 percent. Vibration spectra before and after coupling replacement is shown in Figure 6. The coupling replacement brought down the vibration level from at 1× rpm from 8.0 to 2.0 mils, as shown in Figure 7.

Thrust Bearing Problem in a Large Condensing-Extraction Steam Turbine

A schematic of a steam turbine with thrust and journal bearing [10] is shown in Figure 8. Variations of thrust bearing temperatures, lube oil supply temperature, extraction flow and bearing temperatures under different loading conditions are shown in Figure 9. While the steam turbine and generator bearings indicate near normal operating conditions, very high thrust bearing metal temperatures near the active top side of the thrust bearing can be noticed. However, the bottom side of the thrust bearing does not indicate any alarm condition. It is imperative for a condition monitoring system to not only identify that a bearing problem exits but to isolate the bearing in distress and to what part of the bearing

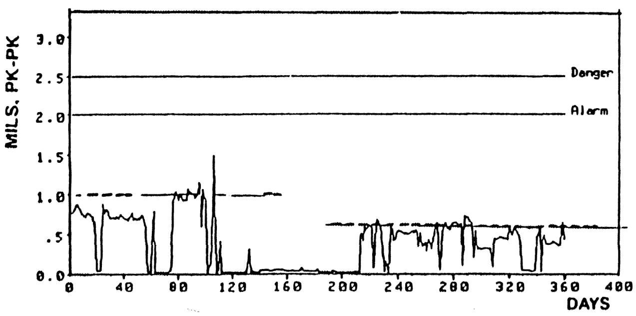


Figure 5. Drop in Vibration Level [1].

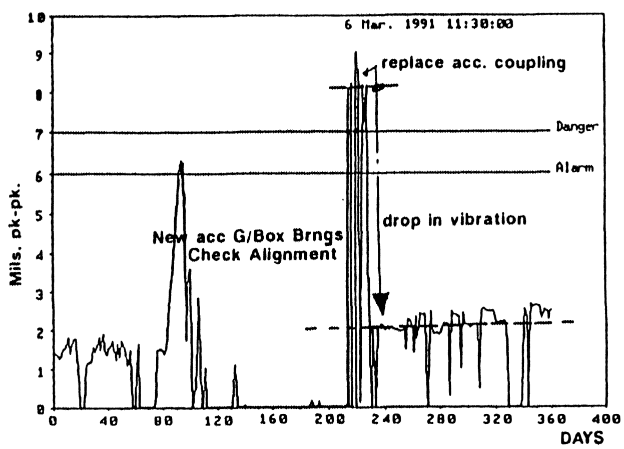


Figure 6. Drop in Vibration Level With New Acc. Coupling [1].

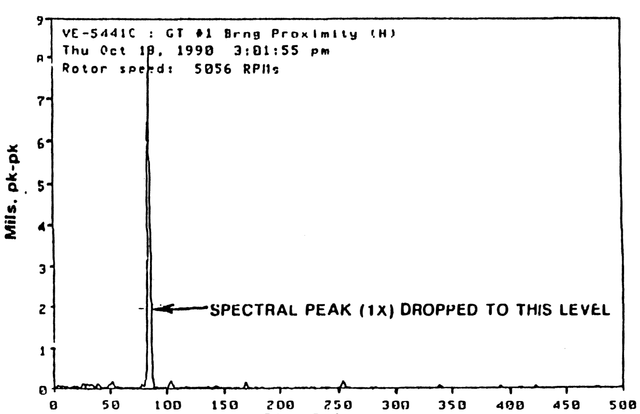


Figure 7. Vibration Spectra Showing High 1X RPM Peak With Old Coupling and Level Arrained Upon Installation of New One [1].

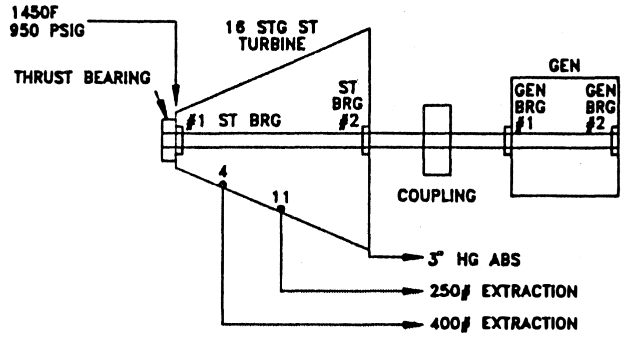


Figure 8. Schematic of the Turbomachinery Train.

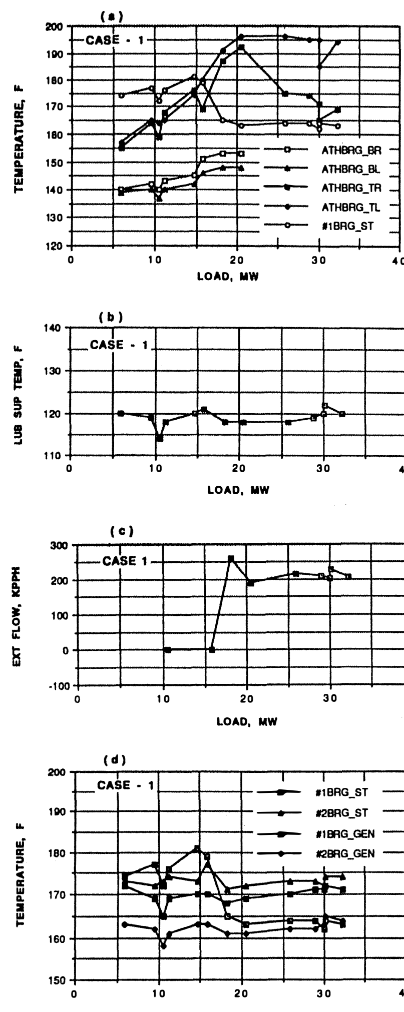


Figure 9. Variation of Parameters Vs. Load.

is causing the problem. In this case, the top and active side of the thrust bearing indicated distress. Since the thrust bearing was newly installed after a major overhaul, additional modifications were found essential to operate the steam turbine at the rated load. This included increasing the five lube oil groves in the upper half section of the bearing by approximately 70 percent and increasing the metal gap on top active thrust bearing side by tapering the shim as shown in Figure 10.

Use of Online Condition Monitoring for Debottle-Necking of a Ethylene Refrigeration Compressor Train

This case pertains to an etheylene refrigeration compressor rated at 7,740 hp unit with sidestreams and driven by a 8000 rpm back pressure steam turbine [11]. As the unit was experiencing a maximum governor situation (i.e., speed could not be increased), it was limiting the process flow. A process design house had performed a debottlenecking study and had suggested that the machine was limited to 8,770 hp. A project to install a new turboexpander was under consideration. This project, if implemented, would have cost approximately $2,000,000.

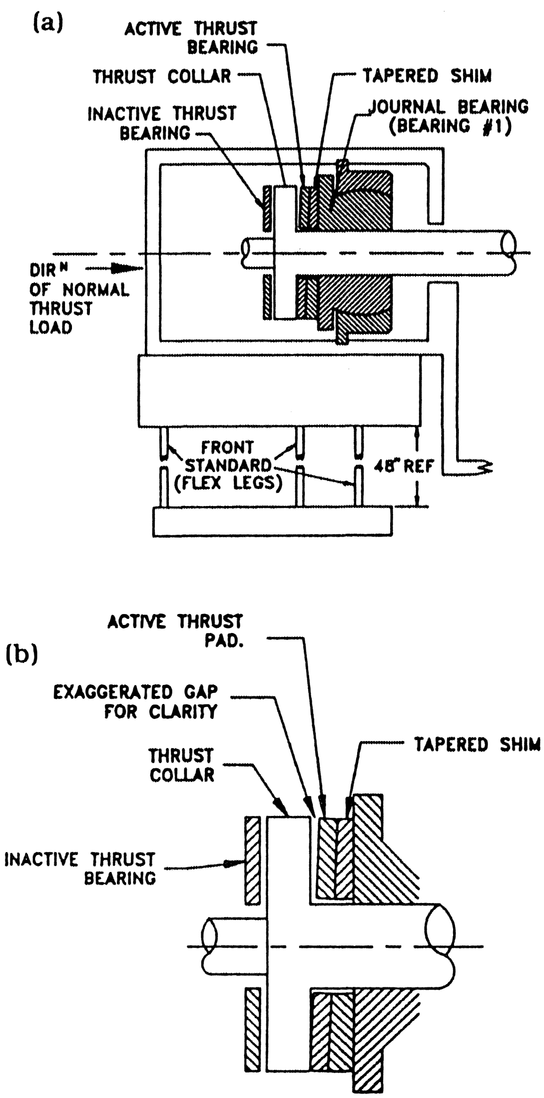


Figure 10. (a) Schematic Showing Locations of the Thrust Bearing No. 1, Bearing and Flexible Legs (Front Standard). (b) Enlarged View of the Gap Between Active Shim and Thrust Collar.

Through the accurate, real time, process data available with the diagnostic computer, it was possible to access the aerodynamic condition of the machine and to recognize the impact that *excessive balance piston* leakage was having on the compressor's running speed. Replacement of the balance piston seal along with other revamping enabled further debottlenecking of the unit to take place.

By examining performance data on the machine, it was determined that the higher than expected speed was the result of a combination of reasons

- High balance piston flows (4000 K lb/hr *vs* a design of 1200 K lb/hr)
- Operation at lower than design suction pressures (0.5 psig *vs* 1.5 psig)
- Off design side flows. For example, due to the condition of the cold box, the compressor was operating a high second stage side load and low third stage side load. As stonewall was approached, there was a rapid fall-off into the third stage resulted in lower gas density, reducing the pressure ratio capability of that stage. These conditions tended to increase machine rpm).
- The compressor's field efficiency was between 60 to 70 percent *vs* a design efficiency of 75 to 76 percent.

Based on these findings, it was decided to open the ethylene gas compressor and replace the balance piston seal. The turbine was not opened. This action resulted in successful debottlenecking of the unit.

This case brings out two important points:

- The importance of aerothermal performance monitoring.
- The importance of monitoring balance line flow. This is not monitored in a majority of installations. The increased balance line flow caused a significant difference in gas density thus affecting the horsepower.

Methane Compressor Turbine Subsynchronous Vibration Problem

This case relates to a subsynchronous vibration problem that was experienced on a 7,370 hp condensing turbine that operated at approximately 8,725 rpm [11]. This steam turbine is coupled to a two body centrifugal methane compressor.

The train had been shut down for upon a startup of the train, an intermittent vibration problem was experienced on the steam turbine. High subsynchronous frequencies (at 0.33 × rpm) were noted. The running speed (1 × rpm) vibration spectral component was also considerable high.

The overall vibration levels would typically jump from below 1.0 mil pk-pk to over 3.0 mil pk-pk and were very unstable in nature. By observing the shaft orbits, observing the historical spectrum plots, and vibration trends a conclusion was drawn that what was being experienced was some sort of looseness in the turbine bearings as opposed to any kind of rotor problem. A decision was made not to tear down the turbine during the shutdown and to only check bearings. Upon disassembly of the bearings, severe fretting between the bearings housings and the bearing holders was discovered and subsequence crush checks revealed up to two through looseness. The bearing themselves were in good shape so the holder was reshimmed with the proper crush and put back. Since then, the turbine has run at its usual low (less than 1,0 mil) vibration level with no sign of any subsynchronous vibrations. Figure 11 shows a collection of vibration plots used for troubleshooting the problem.

Thus, in this case, the condition monitoring system permitted an informed decision to be made not to open up and examine the turbine but to just examine the bearings. It is estimated that this action alone saved $25,000.

Startup Problems of a Gas Turbine Compressor Train

This case pertains to a two-spool gas turbine unit driving a load compressor which experienced starting problems after rebuild. The unit had multiple flameouts during starting, each time in a different can and the problem was identified to the startup schedule and corrected.

Future restarts after the startup scheduler correction indicated unusually low exhaust gas temperature at one thermocouple, indicating a high spread. Swapping of the cans in the burner in the lower temperature sector in question did not reduce the spread levels. Trend plots from condition monitoring system indicated that the low temperature in the thermocouple coincided with power turbine valve (PTV) operation and compressor discharge pressure. In addition, the acceleration levels indicated on the compressor case mounted accelerometers indicated high readings

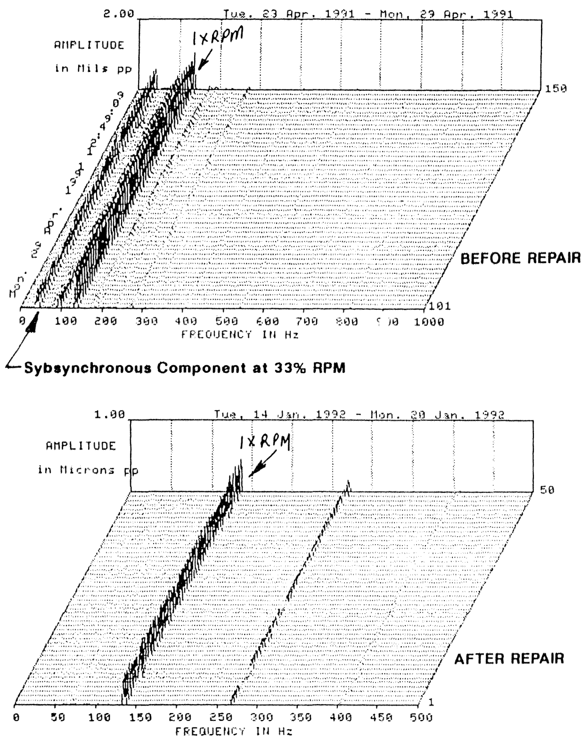


Figure 11. Vibration Cascade/Spectra Showing Subsynchronous Vibration at 33% RPM Due to Looseness [11].

at compressor turbine blade passing frequency and this was the case in power turbine blade passing frequencies as well. Acceleration spectra from the compressor turbine at full load is shown in Figure 12. The spectra clearly indicate that the amplitude of the acceleration is proportional to the loading with 80N1 and 90N1 being the most prominent. The vibration spectra shown in Figure 13 clearly show multiple frequencies and amplitudes which are strongly related to flow related phenomena. The method of spread development and the high acceleration at the blade passing frequencies led to the conclusion that there was most likely air leaks in the combustion gas path. Subsequent inspection revealed a seal trip between two combustor transition pieces and was fixed. Upon restart, there was reduced spread as well as reduced blade vibrations at the blade passing frequencies which had decreased by about 60 percent.

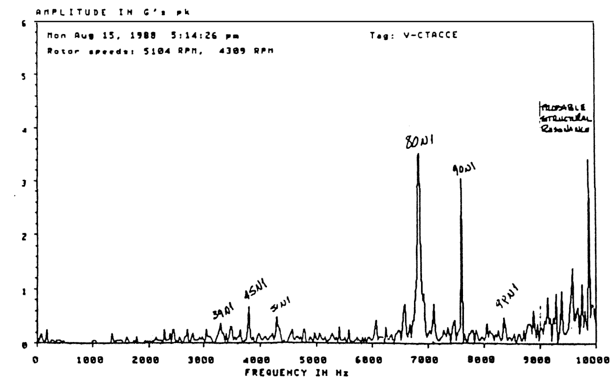


Figure 12. Vibration Spectrum Showing Blade Passing Frequencies.

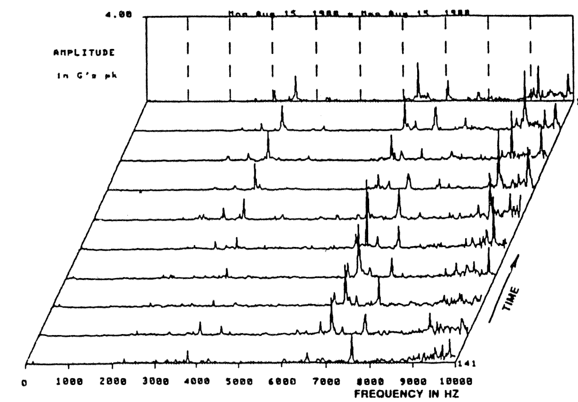


Figure 13. Waterfall Vibration Spectra.

Failure On A Gas Turbine Accessory Gearbox

This case study highlights the interaction of design, operation, and maintenance features. The fundamental problems could not have been averted by condition monitoring because the problems related to improper assembly, and retrofit design.

The integral gearbox was mounted on a 4000 hp gas turbine driving a centrifugal compressor. The accessory gearboxes had experienced a rash of failures. The gearbox was located under the compressor section of the turbine.

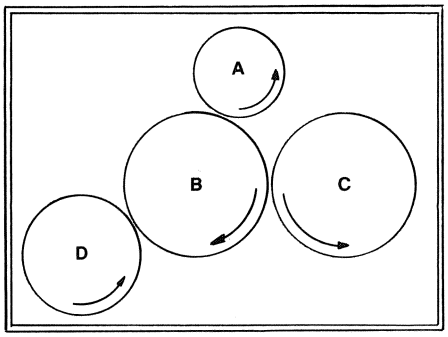
The integral accessory gearbox contained:

- The starter motor, including the gas producer pick up.
- The compressor lube and seal oil pump.
- The gas turbine lube oil and scavenge pump.

These components are driven by their respective drive gears which, in turn, are driving the turbine drive shaft gear through a splined shaft. The input shaft to the gearbox operated at 13,500 rpm as was driven by the turbine gas generator shaft. Figure 14 shows the layout and provides the gear speeds.

After an initial successful run, the gearbox experienced numerous failures with time between failures being as little as a few hundred hours.

A collection of photographs depicting a typical failure are shown in Figures 15, 16, 17, and 18. In most cases, the high speed upper bearing on the input quill shaft holding the pinion experienced the most damage.



GEAR ARRANGEMENT

Gear Designation	DESCRIPTION	RPM	NO. TEETH	PITCH DIA.
A	Turbine Output	13,520	25	2.083"
B	GT Lube oil and Scavange Pump drive	2,991	113	9.417
C	Compressor Lube /Seal	2991	113	9.417
D	Starter Drive	6259	54	4.5

Figure 14. Gearbox Layout & Speeds.

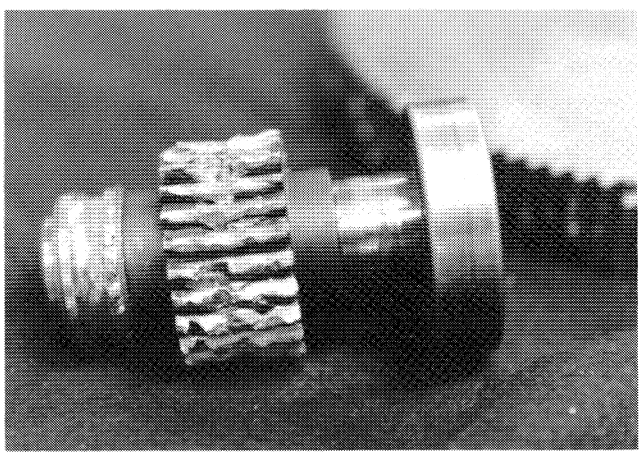


Figure 15. Pinion Gear With Lower Bearing Attached.

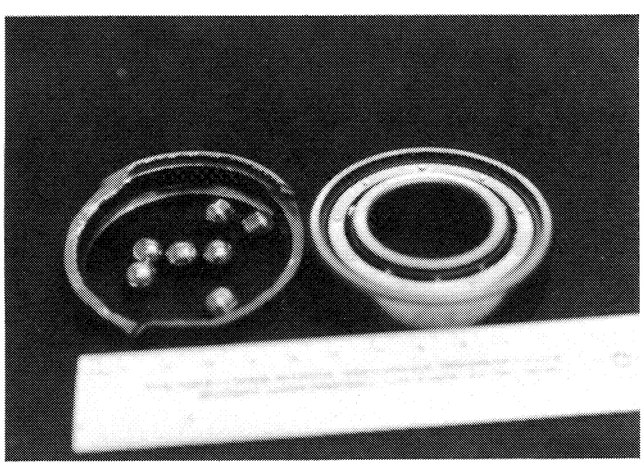


Figure 16. Cracked Upper Bearing Race Along With Physically Intact Lower Bearing. Fractures of This Nature Often Result From Improper Mounting, Insufficient Clearance or Shock Loads.

The failure scenario was as follows:

- The top bearing of the high speed pinion gear progressively failed first. Metal particles fell downward imbedding between the pinion gear teeth and the driven gears.
- The introduction of the metal debris from the bearing imposed additional compressive and shock loads on the high speed pinion gear, causing high bending stresses and fatigue fracturing of the pinion gear teeth due to cyclic bending stresses.
- After the initial failure of the bearing and gear teeth breakage, the damage to the reamining parts accelerated and the quill shaft failed due to additional torsional loading. The quill shaft was seen to have fractured transversely just below one of the splines, due to high cycle fatigue in nature. The initial crack propagation seemed to have been due to alternating torsional stresses, originating in the runouts of the spline cuts; however, the continuing propagation appeared have been caused by rotating bending stresses.

Visual examination of the splines under magnification also showed evidence of fretting, which would indicate some looseness

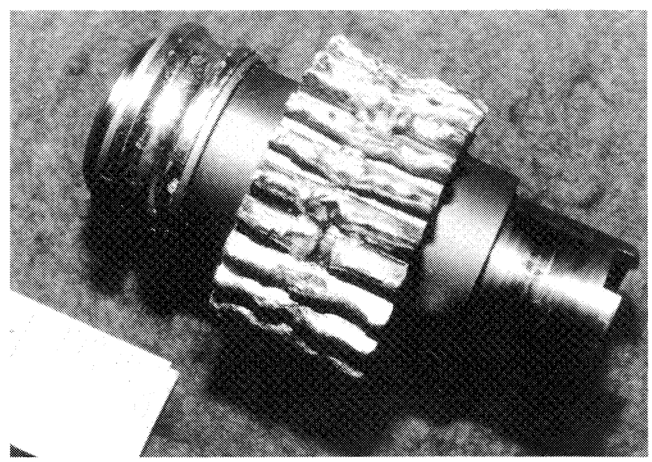


Figure 17. Overall View of the "Pinion Gear, Showing the Inner Race of the Broken-Up Ball Bearing Assembly Still Installed. The Teeth Seen Here Are Badly Mutilated, But None Are Broken Off.

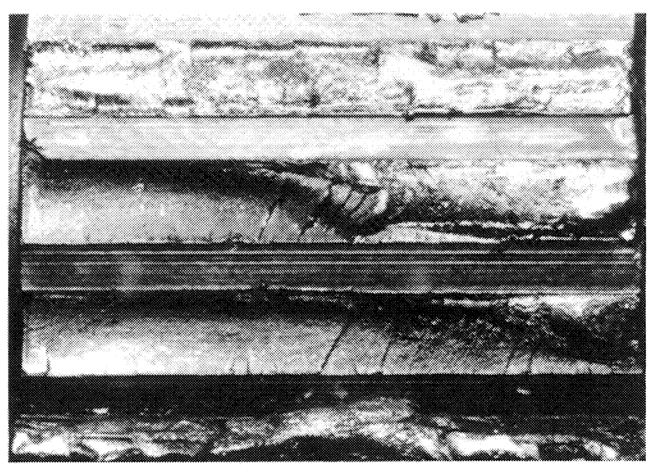


Figure 18. 180° Away From the Teeth Seen Above, Three Teeth Are Seen to be Broken Off at the Root Diameter. The Fracture Surfaces of the Lower Two Exhibit Mutinucleated, High Cycle Fatigue, With Origins Along the Tooth Flank/Root Radii, on the Driver Seals.

in the fit-up. This condition could have contributed to the progressive failure of the bearing from high vibration phenomena, also contributing factors were the observations of questionable fit-up of the bearings.

Because of the rash of failures, it was decided to reverse engineer a complete gearbox. Consequently, a "rebuilt" spare gearbox was disassembled. During disassembly, the following observations were made:

- The high speed pinion system was already experiencing distress. The upper bearing would not turn easily on the shaft and the lower bearing did the same, the upper bearing more severely.

It was obvious that the bearing fit were improper. The ABEC Class 7 bearings are high precision and cannot tolerate improper fits. The interference fit should have been of the order of 0.4 mil. When measured, the interference was 2.0 to 3.0 mils. This was *totally* unacceptable for operation.

- The gear teeth of the pinion also showed signs of intermittent contact and misalignment and distress.
- One dowel pin on the case half was very loose.
- The starter input gear was found extremely worn.
- All the bearings other than the high speed bearings appeared in reasonable condition.
- The most significant observation was that the sleeve for the high speed pinion bearing did not have a 1/32 in oil hole drilled in it.

In studying the history of the gearbox, it was evident that the plant had "copied" the sleeves and this had resulted in the oil hole being "missed". Thereafter when the part was remade, all lacked the oil hole. This error propogated over several rebuilds.

The redesigned gearbox was carefully manufactured with engineering checks and dimensional checks being made through the rebuild process. The gears were also rebuilt. Appropriate bearing fits were utilized and the oil hole was added. The gearboxes have run successfully after the redesign.

FUTURE TRENDS IN CONDITION MONITORING

For large critical unspared machinery several trends in the condition monitoring area seem to be emerging:

- Centralized software and generalized databases being used for multiengine fleet installations. The use of generalized standard software modules permits rapid software tailoring for different engines. Such a concept is currently being implemented at an offshore facility (16 engines and compressor trains) in the North Sea.
- The evolving use of expert systems or shells for numerous *subtasks* such as choice of data compression techniques (information overload), evaluation of alarm levels for diagnosis, and, most important, in integrating inputs from a variety of condition monitoring approaches.
- Integration of condition monitoring systems with multiobjective optimization for maintenance planning.
- Application of a host of new techniques for gas turbine monitoring; specifically pyrometry for monitoring hot section components. Even though this technology is not new, its application in on-line industrial turbine monitoring is rare.
- A recognition of the need to integrate condition monitoring techniques and to tailor the system to failure modes and operational objectives of the plant.
- The use of sophisticated performance degradation models used in conjunction with the condition monitoring to facilitate precise detection of faults and to aid understanding of operational problems such as compressor fouling and erosion.
- The use of transient behavior (both in terms of mechanical and performance) to obtain further insight to machinery problems.

CONCLUSIONS

Several basic types of condition monitoring approaches have been presented. For critical high speed turbomachinery, no one technique can provide all of the answers pertaining to machine condition. An integration of techniques is required and the information obtained by different techniques must be synthesized. Several case studies have been provided to show how integrated monitoring can be of value for reliability improvement and to optimize efficiency consumption. Future directions in the area of condition monitoring have been presented.

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REFERENCES

1. Meher-Homji, C. B. and Cullen, J. P., "Integration of Condition Monitoring Technologies for the Health Monitoring of Gas Turbines," ASME International Gas Turbine and Aeroengine Congress Exposition, Cologne, Germany, ASME Paper No: 92-GT-52 (1992).
2. White M. F., 1988, "An Investigation of Component Deterioration in Gas Turbines using Transient Performance Simulation", ASME Paper 88-GT-258 (1988).
3. Meher-Homji , C. B. and Bhargava R., "Condition Monitoring and Diagnostic Aspects of Gas Turbine Transient Response," Presented at the International Gas Turbine and Aeroengine Congress Exposition, Cologne, Germany, ASME Paper No: 92-GT-100 (1992).
4. Meher-Homji, C. and Focke, A., "Performance and Vibration Monitoring for the Prevention of Gas Turbine Airfoil Failures," 6th Bi-annual ASME Conference on Failure Prevention and Reliability, ASME Vol H-331 (September 1985).
5. Doel, D. L., "The Role of Expert Systems in Commercial Gas Turbine Engine Monitoring," ASME Paper No. 90-GT-374 (1990).
6. Wang, S. S., "Diagnostic Expert System for Industry," Proceedings of the Second International Machinery Monitoring and Diagnostics Conference, Los Angeles, California (1990).
7. Weiskopf F. B., Arcella, F. G., Lin, J. S., and Newmann, R. W., "A Hybrid System Approach for Machinery Monitoring and Diagnostics," Proceedings of the Second International Machinery Monitoring and Diagnostics Conference, Los Angeles, California (1990).
8. Ondryas, I. S., Meher-Homji, C. B., Boehler, P., and Dohner, C., "Durability Surveillance Program on the Advanced Gas Turbine GE Frame 7F," Presented at the International Gas Turbine and Aeroengine Congress Exposition, Cologne, Germany, ASME Paper No: 92-GT-333 (1992).
9. Lakshminarasimha, A. N., Boyce, M. P., Meher-Homji, C. B., " Modeling and Analysis of Gas Turbine Performance Deterioration," Presented at the International Gas Turbine and Aeroengine Congress Exposition, Cologne, Germany, ASME Paper No: 92-GT-395 (1992). Accepted in Journal of Gas Turbine and Power.

10. Bhargava, R. and Meher-Homji, C. B. "Resolution of a Thrust Bearing Overheating Problem in a Large Condensing - Extraction Steam Turbine," paper presented at the 3rd International Monitoring and Diagnostic Conference, Las Vegas, Nevada (1991).

11. Gardiner, J., Mani, G. and Meher-Homji, C. B., "Ten Years of Condition Monitoring Experience On Large Mechanical Drive Steam Turbines in an Ethylene Plant," presented at the 6th International Conference on Gas Turbines in Cogeneration and Utility Industrial and Independent Power Generation., Cogen-Turbo IGTI-7 (1992).